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Technical Note

Romanian Tritium for Nuclear Fusion

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Abstract — *The demand for tritium is expected to increase when ITER (the International Thermonuclear Experimental Reactor) begins operation in the mid-2020s. Romania is expected to detritiate its CANDU (Canada Deuterium Uranium) units at Cernavoda starting 2024, with the goal of improving radiological safety and reactor performance. Detritiation will result in a significant quantity of tritium being produced and thus Romania has an opportunity to supply tritium for fusion. In this assessment, ITER has been used as a reference device requiring tritium, as the projected tritium extraction schedule from Cernavoda aligns favourably with ITER operation. The findings suggest that Romania is capable of providing a total of 6.2 kg of tritium to ITER over its 20 year operation, generating a potential revenue of $186 M (USD). Opportunities associated with the supply of Romanian helium-3 are also considered as a hedging option, which has the potential to generate $120 M (USD) in the case of zero tritium sales. Greater involvement in future fission-fusion tritium-related activities through experience in tritium technologies is also discussed as a unique opportunity for Romania.*

Keywords — *Romania, tritium, ITER, helium-3.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Tritium is a radioactive isotope of hydrogen with a half-life of 12.26 years, which undergoes β-decay producing helium-3. Tritium is rare on Earth, and is produced for commercial use as a by-product of the fission process in CANDU (Canada Deuterium Uranium) reactors through neutron capture in deuterium in the heavy water moderator and heavy water coolant circuit (also referred to as Primary Heat Transport System or PHT) (Ref. 1).

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Tritium present in the heavy water in CANDU reactors can be extracted by means of a TRF (Tritium Removal Facility). Only two accessible TRFs exist worldwide; one in Canada (Darlington) and one in South Korea (Wolsong), together they produce 2–3 kg of tritium a year, which is collected to make up the global tritium inventory.[2] Romania is set to become the third producer of tritium, as it plans to commission a TRF to detritiate its two longstanding CANDU reactors at Cernavoda Nuclear Power Plant.[3,4] The primary motivation for Romania to detritiate is to improve radiological safety, but the production of rare isotopes may also be of significant strategic and financial value.[1,5,6]

Fusion research is expected to generate significant demand for externally sourced tritium in coming years. Although a considerable mismatch between CANDU supply and fusion demand prevents any D-T (Deuterium-Tritium) commercial fusion power programme from depending on CANDU tritium, an external source is still required for the development of fusion technologies. The tritium requirement of ITER (the International Thermonuclear Experimental Reactor) is set to place significant strain on the global tritium inventory when operation begins in the mid-2020s. An assessment of the capability of Romania to contribute to global tritium supply for fusion research may be of great benefit.[2] The capability to handle tritium may also allow Romania to adopt a larger role in future tritium and fusion research, through development of expertise in what is a unique field.

The decay product of tritium; helium-3, is of similar rarity and financial value, but unlike tritium, helium-3 is not radioactive and demand is stable.[7]

Romania has the opportunity to satisfy all of the following considerations:

1. Detritiate to improve safety and reactor performance.[1,3,5]
2. Detritiate to supply tritium for fusion research (including ITER), with a view to increase involvement in future fusion research.
3. Detritiate with a view to potential helium-3 sales as a hedging option.

The decision for Romania to detritiate its CANDU reactors at Cernavoda is currently motivated almost entirely by consideration 1, but the opportunities associated with considerations 2 and 3 should be well understood.

II. TRITIUM FROM ROMANIA

II.A. Romanian CANDU

Around 20% of electrical energy in Romania is provided by two CANDU units at Cernavoda.[8] Unit 1 is nearing the end of its original design lifetime and must be refurbished to extend operation. The most cost-effective option for treatment of tritiated heavy water during refurbishment is to detritiate by means of a TRF (Ref. 5).

II.B. Pilot TRF at ICSI

A pilot TRF was commissioned at the National Research and Development Institute for Cryogenic and Isotopic Technologies (ICIT), ICSI Rm. Valcea for research and development of novel heavy water detritiation technology. Research at the pilot TRF resulted in improvements to the LPCE + CD detritiation process (Liquid Phase Catalytic Exchange + Cryogenic Distillation), as well as facilitating training in TRF operation and safety, as well as cryogenic, chemical and environmental tritium research. The pilot TRF has also supported Romanian involvement in the European fusion research programme.[4,9]

II.C. Rationale for a TRF at Cernavoda

Reducing tritium concentration improves overall reactor performance by increasing isotopic abundance of deuterium in the moderator.[10] It also provides improved safety as research suggests that there is a positive correlation between the tritium concentration in the moderator and overall plant radiological emissions.[1,5,11] Maintaining low tritium concentration reduces hazard to workers, and is estimated to save millions of dollars by eliminating the need for extra safety equipment.[5] Even a minor leak of tritiated heavy water could result in unacceptable radiological exposure to workers, the public or the environment which could result in reactor shutdown, financial and regulatory consequences, and could lead to damaged public opinion.[1,5,10]

A recent study emphasised the financial advantage of a TRF for Cernavoda by considering the alternative option of long-term storage of its tritiated heavy water inventory. It was estimated that storage for 300 years; the time taken for radioactivity to decrease enough for disposal, could cost up to $760 M (USD), which is over four times the cost of commissioning the TRF at Cernavoda, which is expected to cost approximately $170 M (USD) (Ref. 5).

II.D. Cernavoda TRF

Using the Wolsong TRF design as a foundation, and through expert collaboration between CITON (Centrul de Inginerie Technologica Objective Nucleare) Romania; AECL (Atomic Energy of Canada Ltd.)[a]; and other Romanian subsidiaries, an advanced TRF for Cernavoda (CTRF) has been designed. The CTRF uses the same advanced LPCE + CD process as developed by ICIT, in which deuterium and tritium are separated, and the tritium is stored in a secure underground vault.[3,4] The CTRF is capable of reducing and maintaining tritium concentration in the heavy water moderator in both units under a concentration of 10 Ci/kg, which is deemed to be the maximum allowable tritium concentration after the detritiation process.[3,4,12] The design is currently under review by Romania's nuclear regulator having been finalised in 2015 after additional safety measures were considered following the Fukushima accident in Japan, 2011.

The 10-year strategy for Cernavoda owner SNN (Societatea Nationala Nuclearelectrica) is to maintain nuclear

[a] AECL CANDU reactor designs is now licensed to CANDU Energy (SNC-Lavalin).

capacity whilst prioritising nuclear safety and security. SNN intends to advance with refurbishment of Cernavoda unit 1 between 2023 and 2025, and the CTRF is expected to begin detritiation in 2024 to coincide with the refurbishment.[8]

II.E. Cernavoda 3 and 4

Romania is expected to double its nuclear capacity by completing the build of two additional CANDU units at Cernavoda.[11] Although research suggests it is feasible to service all four reactors using the CTRF, projected operation of units 3 and 4 is unlikely to align with the current CTRF schedule and is thus considered to be out of scope.[12] An additional TRF to service units 3 and 4 is being considered at Cernavoda as a separate project (CTRF-2) (Ref. 11).

III. TRITIUM FOR FUSION

III.A. Romanian Tritium for Nuclear Fusion

No external source of tritium could sustain a D-T magnetic confinement fusion power programme, but until successful tritium breeding technology is developed, fusion research will require an external source of tritium. Romania will become the third producer of commercial tritium worldwide and may be capable of supplying significant quantities for fusion research when the CTRF is commissioned in 2024.

The supply of tritium from Romania could be financially significant as the price of CANDU tritium is estimated at $30 M (USD) per kilogram,[b] but the fact that tritium undergoes radioactive decay and demand is uncertain makes the supply paradigm entirely unique.[2,5,13] SNN and Romania are unlikely delay detritiation for the benefit of fusion research, as potential tritium sales are seen only as a convenient by-product to the primary aim of improving safety. However, delay to commissioning of the CTRF originally due in the mid-2010s may have positive effect on ITER operation, and thus on corresponding tritium sales for Romania.[c] Although entirely separate projects, forecasts suggest that tritium production from Romania's CTRF aligns favourably with the expected start of ITER operation. ITER will begin operation in 2027 three years after the CTRF; coinciding with the period of highest tritium yield (see Sec. V.A).[14] The benefits would be twofold: Romania could see almost immediate demand; and an additional source of tritium would be readily available for fusion research experiments, namely ITER.[d]

ITER requires a total of 18 kg of tritium over its planned 20-year operation and will depend entirely on an external source for operation, and it is currently envisaged that tritium will be sourced from Darlington TRF in Canada, which has the largest inventory of tritium.[1,2] Although Romania may never actually supply tritium to ITER, other fusion research worldwide; both private and public, is expected to require tritium on a similar timescale and could look to source it from Romania.[e] In a hypothetical future market for Romanian tritium, capital costs for the CTRF could be co-funded by third party fusion-based investors in return for a share of the tritium produced. Increased involvement of the fusion community in the CTRF project could also provide the basis for greater cohesion between fusion and fission communities.

III.B. Fission-Fusion Opportunities

There are inherent opportunities for fission-fusion crossover associated with current and future tritium activities in Romania. Romania is actively involved in the EURATOM fusion programme, and the pilot TRF at ICIT is used directly for ITER research, but Romania also has the capability to support future fusion activities, including involvement in private ventures.[15] Romania is developing a new generation of skilled professionals for future research, and is involved in Tri-TOFFY (Tritium Technology for Fusion Fuel Cycle), and the TriPla-CA consortium (a consortium of four EU laboratories) which carries out research, development and design work for ITER on tritium related activities.[9,12,15,17]

[b] Tritium pricing is not publicly available. The most recent literature cites tritium at $30 M (USD) per kg, and thus this is deemed to be the most accurate estimation.[2,5,13]

[c] Annual tritium demand from non-fusion industries is estimated at 200 g. Tritium for fusion does not make up the entirety of market demand.[2]

[d] Supply of Romanian tritium to ITER is hypothetical, and does not reflect the views of the Romanian government, SNN or the ITER organisation. ITER's tritium schedule is used as a reference to highlight the potential for future isotope sales from Romania, which could be used to supplement fusion research devices requiring tritium. It is not suggested that Romania should, or will supply ITER with tritium.

[e] Although tritium is not classified as a Special Nuclear Material, future supply of tritium from Romania must comply with international nuclear policy and law. Romania is a party to the Nuclear Non-Proliferation Treaty (NPT), and is a member of the Nuclear Suppliers' Group, and as such is bound to conform to IAEA standards.[16]

Given the similarities between TRF and fusion tritium technologies, expertise developed through future operation of the CTRF will allow for even greater understanding of safety, recovery and storage of large quantities of tritium, and will thus increase the attractiveness and ability of Romania to adopt a major role in future fusion research.[3,6,9]

The real-world issues associated with handling large quantities of tritium in future fusion power plants are largely unknown, and the effects of issues such as accidental tritium release can only be assessed using knowledge from fission tritium experience.[1] An additional consideration is in the security of tritium storage, and prevention of the proliferation of nuclear material. Experience from the storage of tritium at Darlington TRF will be viewed as a precedent for security requirements, which will help to resolve Romanian licensing concerns, but further experience from Romania can in turn be used to improve the security of future fusion facilities storing tritium for fuel.[1]

There is a great need to exchange knowledge to aid development of future tritium activities and Romania's involvement in both fission and fusion research puts it in a leading position to provide a bridge between the two communities.[1]

IV. HELIUM-3 CONSIDERATIONS

Helium-3 is currently produced from the decay of tritium produced for military use in the U.S.A. and Russia.[f] The terrorist attacks on the U.S.A. on September 11th, 2001 triggered a sharp increase in demand for helium-3 from the security sector for use in neutron detection, and demand now far outweighs supply capability. The market remains balanced only by stockpiled helium-3 from the latter part of the 20th century.[g,7]

Large uncertainty surrounding the future of helium-3 supply has seen recent consideration for the supply of helium-3 from CANDU TRF storage. The U.S. Department of Energy has approached Ontario Power Generation, Canada, over the possibility of helium-3 extraction from Darlington TRF, which is estimated to have accumulated around 100,000 litres (at standard temperature and pressure) of helium-3 over its 25-year operation. The quantity of helium-3 within the Darlington TRF is significant enough to replenish the current inventory.[7] However, a similar opportunity may exist for partnership between the CANDU-TRF countries of Canada, South Korea and Romania to address any future helium-3 shortage, particularly when considering the potential increase in demand for helium-3 from D-^{3}He fusion research.[7]

Growing scarcity of resource has seen the commercial price of helium-3 increase to $2,750 (USD) per litre (at standard temperature and pressure), equating to approximately $20,000 (USD) per gram.[h,5,7,18] Given that the total cost of retrofitting a helium-3 extraction and storage facility onto the CTRF site is estimated at $11 M (USD), Romania should consider the prospect of helium-3 sales.

V. ANALYSIS

V.A. Method and Results

In 2011, the tritium concentration in the heavy water moderator of Cernavoda units 1 and 2 was 54 Ci/kg and 20 Ci/kg respectively. Given the estimated increase in tritium concentration of 3.7 Ci/kg per year in the heavy water moderator of an average in-service CANDU reactor, tritium concentration is expected to have reached equilibrium at roughly 80 Ci/kg in unit 1 by 2024, at the start of CTRF operation.[3,5,10]

Due to the total volume of moderator and coolant in each CANDU unit,[i] and CTRF processing capacity,[j] approximately 2 years is required to reduce the initial concentration to 10 Ci/kg in each unit. Thereafter tritium concentration will be maintained below 10 Ci/kg by alternating between Cernavoda units 1 and 2 on a

[f] Although now diminishing rapidly, until recently the largest source of helium-3 been from the stockpile of decaying tritium for military use from the U.S.A. and Russia.

[g] The difference between tritium produced military use and that produced for civil use is in the method of production, as both sources are isotopically, physically and chemically identical. Tritium for military use is produced in dedicated breeder reactors, and international safeguards prevent it being used for civil purposes. Similarly, tritium produced from CANDU is prohibited from being used for military purposes. The importance of this is in that unlike tritium, the resulting decay product; helium-3, is not safeguarded as a nuclear material, and is permitted for civil use.

[h] Helium-3 for federal use in the U.S.A. is sold at a price approximately one third of the commercial price. Price of future Romanian helium-3 may differ.

[i] One CANDU unit has an inventory of 530 M g heavy water, this inventory includes: 200 M g for the PHT; 270 M g for the moderator; and 60 M g surplus for loss make-up.[5]

[j] It is assumed that the CTRF will run for 6500 hours per year, processing 40 kg heavy water per hour, meaning a total of 265,000 kg heavy water is processed per year. This is defined in the CTRF specification.[4,11]

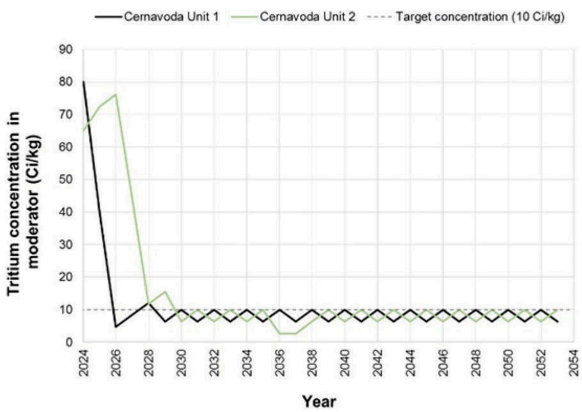

Fig. 1. Tritium extraction schedule of CTRF (adapted from Ref. 3).

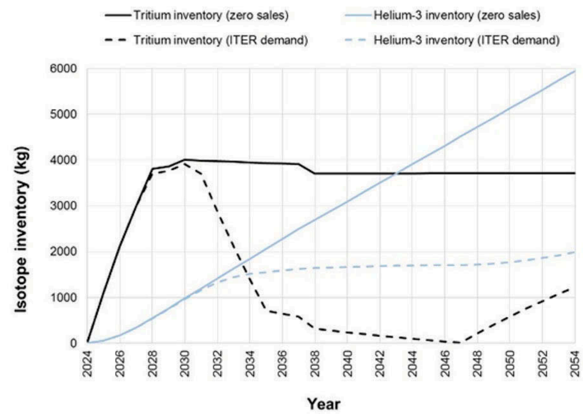

Fig. 2. Projected isotope inventory of CTRF.

one-year cycle,[k] meaning that peak tritium recovery is expected during the first 4 years of operation.[12] Unit 1 will begin detritiation in 2024, and by the start of the detritiation of unit 2 in 2026, its concentration is expected to have reached 72 Ci/kg.

Unit 1 is expected to undergo refurbishment for life extension over a two-year period coinciding with detritiation starting 2024,[l] and refurbishment of unit 2 is expected a decade later in 2035.

The CTRF processing capacity together with the projected tritium concentrations calculated as shown in Fig. 1 were used to determine the tritium extraction schedule and corresponding mass quantity of tritium extracted each year. The quantity of tritium decaying from the inventory was used to produce the values for yearly helium-3 inventory. The graph in Fig. 2 shows the growing isotope inventory over 30-year operation of the CTRF.

The hypothetical scenario that Romania could provide tritium to ITER was also analysed. Figure 2 shows how the Romanian tritium inventory may be affected by supply to ITER. Theoretical quantities of tritium to be supplied were determined using the tritium schedule for ITER from Ref. 19, but the dates have been adjusted to match current estimates for the operational start of ITER from Ref. 14.

[k] Tritium concentration in the PHT reaches a maximum of 2–3 Ci/kg (Ref. 5), but for this assessment tritium concentration is assumed to be zero. However, the entirety of the 530 M g inventory from one CANDU unit must still be detritiated through the CTRF, and the subsequent diluting effect and the increased detritiation cycle time are taken into account.

[l] It is assumed that unit 1 will undergo a two-year detritiation cycle of its heavy water whilst in an offline state during refurbishment.[5]

V.B. Discussion

The tritium recovered over the first 4 years of operation generates a base inventory of roughly 4 kg. The inventory remains in a near-constant state at this level until a slight decline is caused by refurbishment and resulting offline state of unit 2.[m] Helium-3 inventory increases with time, and could be supplied at an average rate of 1,500 litres (at standard temperature and pressure) per year in the event of zero tritium sales, generating total revenue of around $120 M (USD) over the 30-year operation of the CTRF.

Romania has the capability to match ITERs tritium requirement for the first three tritium test phases (fuel cycle systems testing, integrated commissioning, and 4 years pre-testing). Thereafter, Romania could afford supply of around 20% of the yearly tritium requirement for the remaining ramped-up test phase. Romania could therefore supply a total of 6.2 kg of tritium to ITER, equating to revenue of $186 M (USD), given a tritium price of $30 M (USD) per kg (Ref. 2). Supplying tritium to ITER causes helium-3 inventory to plateau until ITER operation ends. However, Romania may still have the capacity to supply smaller quantities of helium-3 in addition to tritium sales, which could generate a surplus of $40 M (USD) over the operational lifetime of the CTRF (given helium-3 priced at $20 M (USD) per kg), bringing total revenue from isotope sales to over $225 M (USD) (Ref. 18).

[m] It is assumed that unit 1 does not undergo a two-year cycle during unit 2 refurbishment, and isotope production is set to zero for the year 2035. It is assumed that maintenance to the CTRF itself will be carried out in this period.

VI. CONCLUSION

Aligning projections of the tritium schedule from operation of the CTRF with expected ITER demand shows the potential for Romania to supply tritium for fusion research. Romania could generate significant revenue from the sale of tritium, but may also see greater participation in future tritium related research activities in both fission and fusion as a result of its well-established tritium research capability, and corresponding experience in operation, safety and security. Prospects associated with the potential supply of helium-3 to an already strained market provides a unique hedging option in the case of zero tritium sales, and merits consideration in future policies.

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